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Study on a Coal-Fired Power Plant with CO_2 Flue Gas Scrubbing

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Abstract

An analysis of the integration of a capture process with a coal-fired power plant was conducted, including part of the CO_2 conditioning for its transport. For this purpose the simulation of the capture plant was undertaken with the help of Aspen Plus and the power plant with EbsilonProfessional.

Keywords: CO_2 capture; MEA; absorption; integration; power plant.

1. Introduction

With the increasing necessity to reduce anthropogenic CO_2 emissions, it has become clear that existing and new technologies for the purpose of electric power generation with coal have to be further developed, due to the fact that this sector accounts for a large source of CO_2 emissions [1]. As presented in several documents [2, 3, 4], there are three main categories for capturing CO_2 from power plants' flue gases: Pre-combustion, Oxyfuel and Post-combustion.

It is well known that Post-combustion capture results on high net efficiency penalties, which is the reason why the German research program (like COORETEC) initially omitted this option as an alternative to mitigate the emissions of CO_2. However, Post-combustion offers the prospect of retrofitting an existing power plant, and considering that in Germany approximately 51 % of the generated electricity comes from coal-fired power plants [5] makes this, an attractive CO_2 reduction strategy. In addition, the life cycle of several power plants is coming to an end, not only in Germany, but in Europe (EU-25) in general. According to [5] up to 200 GW power plants' capacity will have to be replaced by 2020 and 100 GW more will have to be added, to be able to meet the increasing energy demand. If CO_2 emission's reductions are to be met, as established in the Kyoto protocol, then all possible efforts will be needed in order to fulfil this task, and Post-combustion capture will most definitely not be the exception.

Although there are already several commercial technologies for the separation of CO_2, flue gas scrubbing with amines projects itself as the most promising one when it comes to a large scale application, like a 500 MW power plant or bigger. A reason for this is the large experience behind this process thanks to its former –and current– use in the oil industry for EOR. Nevertheless, it has long been since substantial progress was made with respect to the development of new solvents. The main problem is the amount of energy they require for their regeneration, which is the major power plant's efficiency drawback. Another hitch for this technology is the fact that the biggest existing commercial plants are designed to capture a maximum amount of 1000 t/d in the case of EOR, 800 t/d for chemical industry and 300 t/d in the food industry [6]. This number is too

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small for a power plant like the Reference Power Plant NRW (RPP NRW), in which case approximately 8000 t/d of CO_2 would have to be processed for a capture rate of 90 %.

While a lot of the research concerning the CO_2 capture has already been done, there are still some obstacles to overcome, before "near zero emissions' power plants" can actually be built. These include particularly integration of the capture with the power plant. Furthermore, once the CO_2 has been successfully separated from flue gases, it still has to be conditioned for its transport to the location of the sequestration field. This process also takes place at the power plant itself, resulting in another efficiency penalty.

2. MEA absorption

The absorption process was simulated assuming that the process configuration had not yet been optimised. With configuration is meant the way absorber and stripper columns are connected with one and other. Indeed the process configuration has previously proved itself as an important factor to be considered in the capture process [6, 7, 8]. Nonetheless, this work considers the integration of both plants and does not focus on the optimisation of the absorption process. The key parameters needed from the simulation are: Composition of the flue gas, reboiler temperature, cooling water requirements, CO_2 temperature and composition of the CO_2 stream.

The simulation was undertaken with Aspen Plus, as a rigorous model with the property method ELECNRTL and the chemistry package MEA-CO2 from the same program.

In order to get consistent results from both simulation tools (Aspen Plus and EbsilonProfessional) the same kind of coal had to be used. Table 1 shows its composition.

According to the literature KS-1 (a sterically hindered amine) requires less energy of regeneration than MEA. This would make KS-1 a good candidate for a CO_2 capture plant. However, this solvent is still been developed – although there already exist two commercial plants – and any information regarding it remains confidential. Thus the simulations will focus on a 30% MEA solution. Another reason for this is that MEA is very often used and therefore represents a good reference to compare the progress or trend in capture processes.

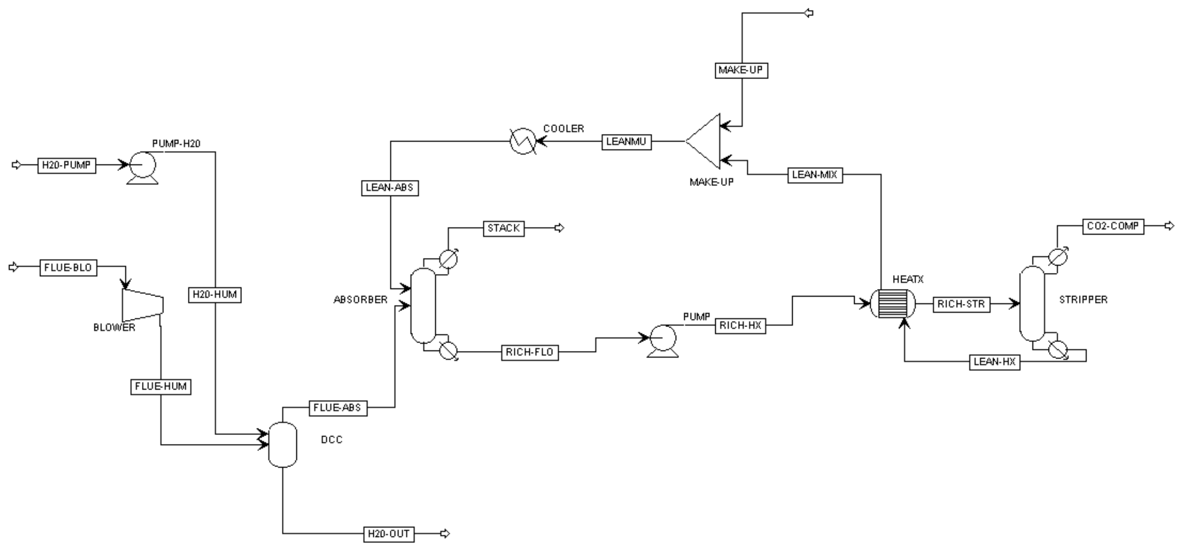

Figure 1: Scrubbing Process Configuration

Table 1: Coal data used for this study (water and ash free)

Coal composition	**Mass fraction**
Carbon	0,834
Hydrogen	0,045
Oxygen	0,094
Nitrogen	0,0191
Sulphur	0,0076
Chlorine	<0,0001
Sum	0,9998
Ash (raw condition)	0,14
Water (raw condition)	0,075
Volatile matter	0,30
Calorific value (raw condition) [MJ/kg]	25,95
Lower heating value (raw condition) [MJ/kg]	25,00

The absorber column was simulated under atmospheric conditions and considering a pressure loss of 80 mbar along the column. In order to compensate this, a blower was built before the absorber and direct contact cooler (DCC) respectively. The inlet temperature of the flue gas in the absorber was set to 40°C. The same temperature corresponds to the solvent at the absorber inlet. A temperature of 47°C was assumed for flue gases before they are cooled down in the DCC drum. This implicates that flue gases have previously been treated in the DENOX and FGD plant. It was also assumed, that flue gases have also been treated in a second FGD plant, with the purpose of keeping the suggested levels of SO_2 to prevent degradation of the solvent [6, 8, 10]. This plant is not shown in Figure 1. Since the cooling water within the scrubbing system would be provided by the power plant itself, its temperature remains the same (15°C correspond to the average ambient temperature in Germany). The stripper has a pressure of 1,6 bar at the top of the column and 1,96 bar at the bottom.

3. Reference Power Plant NRW

Within the next years several coal-fired power plants will be built in Germany. The technology of such plants is that of the Reference Power Plant NRW (RPP NRW) with an efficiency (LHV) of 45,9 %. It is possible to reach higher efficiencies (approximately 48 %) depending on the location of the power plant. This is usually associated with cooling water from a see or a river. However, given that the majority of the power plants would work with a cooling tower, it makes sense to simulate the integration of such plants under these conditions. The most important parameters of RPP NRW are summarised in Table 2.

Table 2: Design data of RPP NRW [9]

Gross Output	600 MW_{el}
Net Output	555,6 MW_{el}
Net Efficiency	45,9 %
Main Steam	285 bar 600°C
Condenser Pressure	45 mbar
Pre-heating Stages	8

4. Process integration

In order to get the CO_2 capture plant to work, the links between the scrubbing process and the power plant itself have to be identified first. In this case, the most important one corresponds to the steam supply for regeneration of the solvent.

For RPP NRW the steam will be extracted before it is directed to the LP Turbines (T=217°C, p=3,6 bar) and reinjected between the second and third Feedwater preheaters (T=100°C, p=3,6 bar). A pump was built in the simulation (not shown in Figure 2) to compensate the pressure losses that would result from this connection. This measure helps to prevent an imbalance within the power cycle. The temperature and pressure of the extracted steam guarantee its use for both reclaimer and reboiler of the scrubbing process.

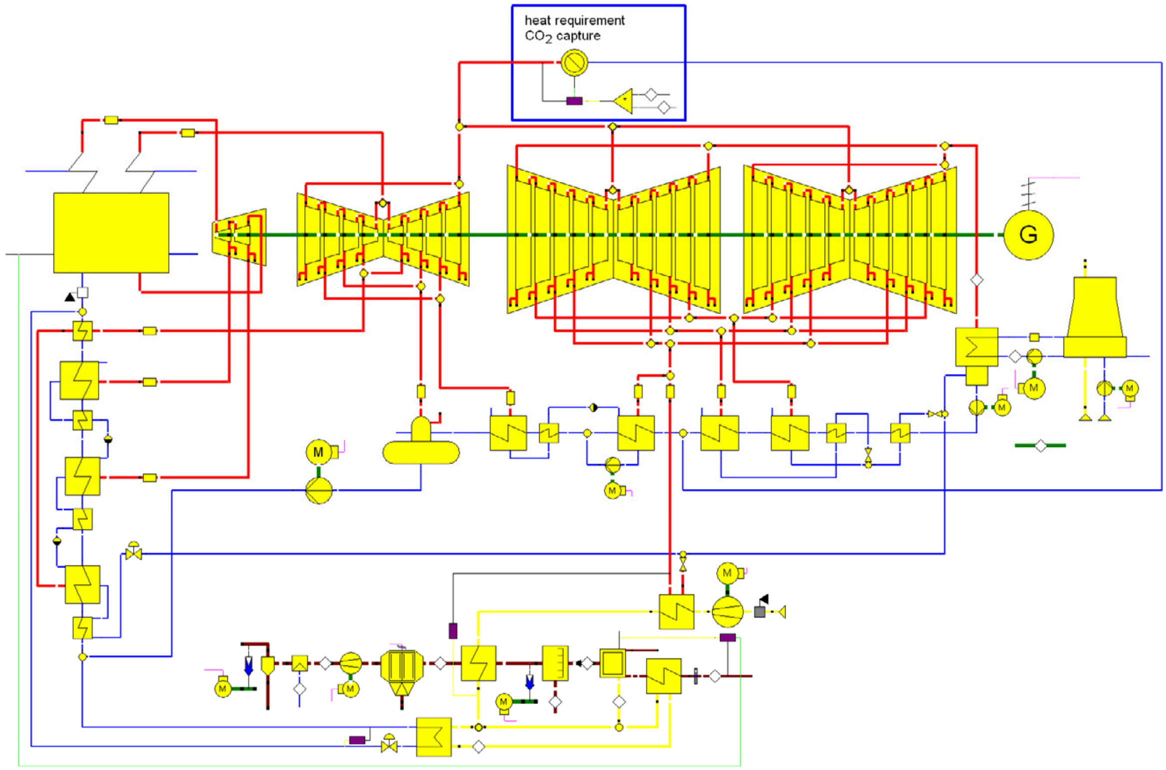

Figure 2: Reference Power Plant NRW with integrated CO_2 Capture

5. CO_2 compression

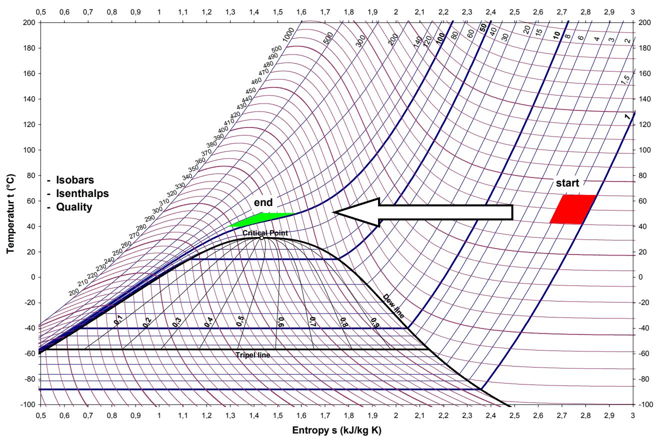

Figure 3: CO_2 Compression: start (red) and end (green)

In addition to simulation of scrubbing process and its integration with the power plant, the first considerations regarding the compression of the captured CO_2 were analysed. Not only does the power plant have to supply the energy for the capture process, but it also has to supply the energy for the compression of the CO_2 for transport purposes. It is therefore important to have an idea of how this process is going to affect the power plant in terms of efficiency penalties due to the electricity needed by the compressor(s) and the amount of cooling water required for this.

It was decided to analyse how many stages would be required to reach a pressure of 100 bar and a temperature of 40°C. Under these conditions the CO_2 is at supercritical state. For transport purposes the pressure must be further increased until up to e.g. 200 bar depending on the pipeline length and the conditions of

CO_2 storage site. The ranges for compression start and end assumed for the examination can be seen in Figure 3. The starting point represents the CO_2 coming from the top of the stripper column. For this analysis it was also assumed, that the CO2 stream has been cooled down to a temperature between 40°C and 50°C. The number of compressor stages considered varies from 1 to 6 and the pressure ratio between stages is constant.

The simulation tool EbsilonProfessional was used for the first approach of the calculations. It is however important to mention that this program has limited resources when it comes to data on chemical media. For this reason a pure stream of CO_2 was considered for compression. Aspen Plus can be used in order to avoid this kind of uncertainties. This program counts with a wide range of data and would not only be able to simulate the scrubbing system, but also the compression of the captured CO_2 with a few impurities.

6. Results

Due to the solvent's temperature of regeneration and the temperature of the steam needed for the reclaimer in the absorption process, the minimum pressure of the bleed is 3,6 bar. This means, that the steam has to be extracted before it reaches the low pressure turbines. The required amount of heat of the RPP NRW amounts 412 MWth for an average capture of 103,1 kg_{CO2}/s, which corresponds to a 90 % capture. The amount of steam needed for the regeneration process varies from 132,7 kg/s until up to 177 kg/s depending on the specific heat demand of the scrubbing process (3-4 MJ/kg_{CO2}). A throttle would have to built before the low pressure turbine for the purpose of maintaining the required 3,6 bar in the steam pipeline. This option makes the power station flexible to capture CO_2 or not. Nevertheless, a throttle also brings losses with it (e.g. Δh=100 kJ/kg, but this value varies strongly depending on the configuration of both power plant and scrubbing system) so that the overall net efficiency of the power plant still is affected in an irreversible way.

For the analysis of the compression part, three different pressures at the top of the stripper column were considered. Figure 4 shows the results of these pressures and the amount of energy required per stage in kW/kg_{CO2}. As can be seen in this figure the required energy decreases with an increasing number of stage. The minimum number of stages recommended in this case would be four. How many stages will actually be used in a CO_2 compressor is a matter of economics. From Figure 4 a compressor with six stages (see Figure 5) would result in a minimized specific energy demand, but in order to see if this would be a viable option a techno economic analysis would have to be conducted. This work did not focus on the economics of the process.

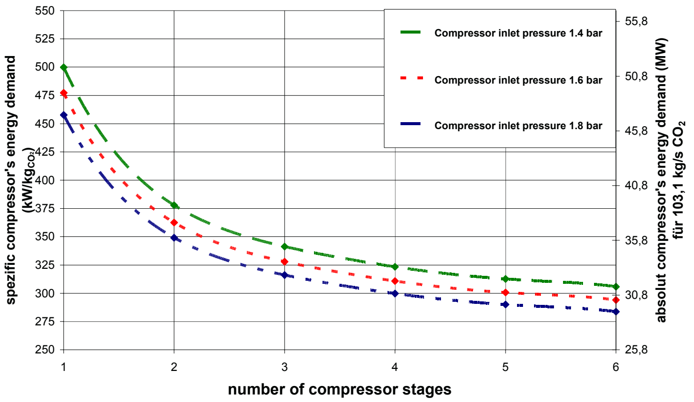

Figure 4: Compressor capacity

As previously mentioned for the first approach calculations of a CO_2 compressor it was assumed that the stream consisted 100 % of CO_2. In reality this would not be true. Since the CO_2 would come from the resulting flue gases of coal combustion, a certain number of impurities is to be expected in the CO_2 stream coming from the top of the stripper column. Another important point is the fact that some water might still be present in the same stream. In order to avoid corrosion problems it is recommendable to have the least possible amount of water. Figure 6 shows the solubility of water in CO_2 [11]. According to it, the lowest solubility of water in CO_2 occurs at a pressure before the supercritical stage of CO_2 has been reached. This point (see Figure 6) would be the optimum state to dewater the CO_2 stream. In Figure 5 the dewatering point would be before entering the last compression stage, in this case the 6th one. Figure 6 also shows a dotted line which represents the displacement of the original curve when impurities are present. As a matter of a security measure the start and end point of the 6th stage could be moved downwards and upwards respectively. An important remark here is that Figure 6 is valid for a CO_2 temperature from 24°C to 28°C and the example considered in this study contemplates a temperature of 40°C. The difference would be that the presented curve from Figure 6 would slide upwards, but the trend of the curve would remain the same. The opposite would be expected if the CO_2 temperature would be lower than 30°C.

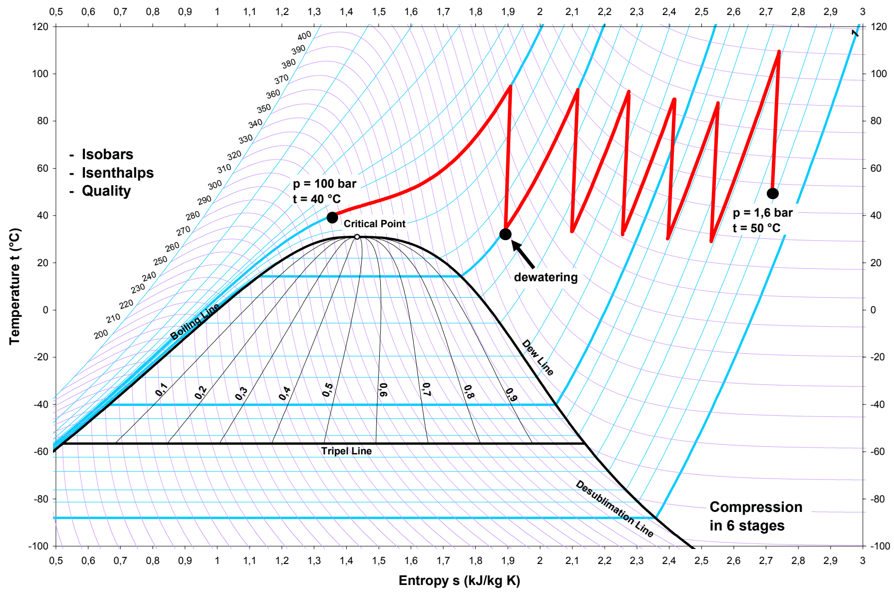

Figure 5: CO_2 Compression in 6 stages in t-s diagram

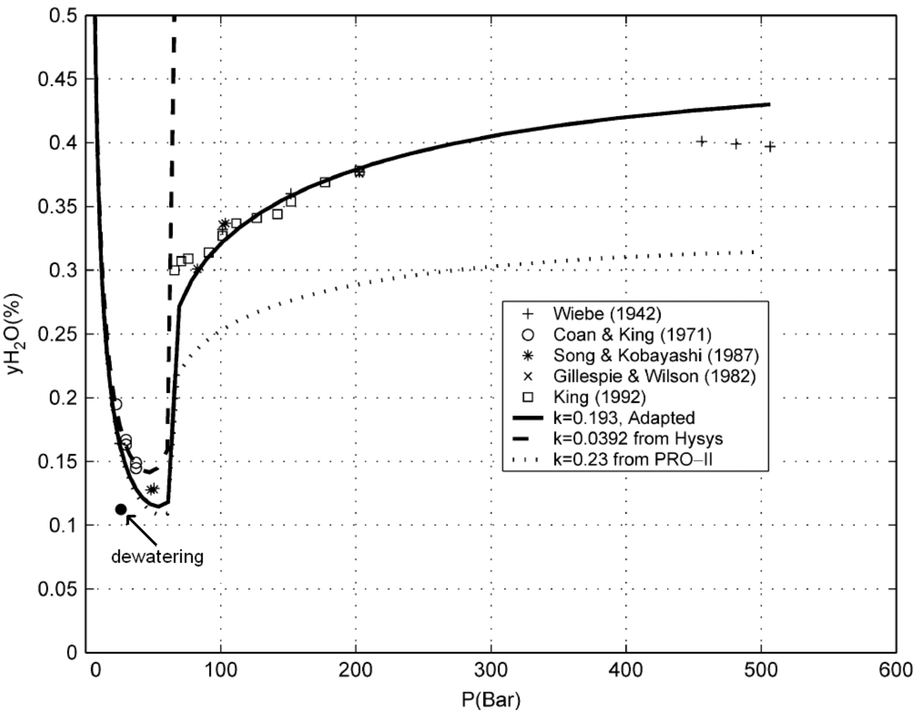

Figure 6: Solubility of water in CO_2 from 24°C to 28°C [11]

7. Conclusions

The simulation of the scrubbing process with Aspen Plus helped to establish the conditions needed to provide the required energy for the regeneration from the power plant. Due to the energy demand from a scrubbing system using MEA as a solvent with 90 % CO_2 capture, it is not possible to extract the steam of the power plant without affecting it permanently. The pressure decreases in the steam pipeline as a result of the steam extraction. This can be controlled by building a throttle in the steam pipeline but would also provoke irreversibilities. Regarding the compression it is recommended to use at least four stages to get the CO_2 to supercritical stage. The dewatering of the CO_2 stream should take place before entering the last compression stage.

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